From architectured materials to the development of large-scale additive manufacturing

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Architectured materials are a rising class of materials that bring new possibilities in terms of functional properties, filling the gaps and pushing the limits of Ashby's materials performance maps[1], as shown on Figure 1 for the specific flexural rigidity of plates. The term architectured materials encompasses any microstructure designed in a thoughtful fashion, such that some of its materials properties have been improved in comparison to those of its constituents, due to both structure and composite effects, which depend on the multiphase morphology, i.e. the relative topological arrangement between each phase[2].

There are many examples: particulate and fibrous composites, foams, sandwich structures, woven materials, lattice structures, etc. One can play on many parameters in order to obtain architectured materials, but all of them are related either to the microstructure or the geometry. Parameters related to the microstructure can be optimised for specific needs using a materials-by-design approach, which has been thoroughly developed by chemists, materials scientists and metallurgists. Properties improvements related to microstructural design are intrinsically linked to the synthesis and processing of materials and are therefore due to micro and nanoscale phenomena, taking place at a scale ranging from 1 nm to 10 μm. This scale is below the scope of the present project work, in terms of topology optimisation, but has been extensively studied in the literature[3].

Processing is the key technological issue for further development of architectured materials, and progress is made every day in this direction, as it was done in[4] by using a sequence of several processing techniques in order to fabricate ultralight metallic microlattice materials. From a macroscopic viewpoint, parameters related to the geometry have mainly been the responsibility of structural and civil engineers for centuries: to efficiently distribute materials within structures. An obvious example would be the many different strategies available for building bridges. At the millimetre scale, materials can be considered as structures, i.e. one can enhance the bending stiffness of a component by modifying its geometry while keeping the lineic mass (for beams) or surfacic mass (for

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[1] M. Ashby, Designing Architectured Materials, Scripta Materialia, vol. 68, no. 1, pp. 4-7, 2013.
[2] Ibid. and M. F. Ashby and Y. Bréchet, Designing hybrid materials, Acta Materialia, vol. 51, pp. 5801-5821, 2003.
[3] D. Embury and O. Bouaziz, Steel-Based Composites: Driving Forces and Classifications, Annual Review of Materials Research, vol. 40, pp. 213-241, 2010.
[4] T. A. Schaedler, A. J. Jacobsen, A. Torrents, A. E. Sorensen, J. Lian, J. R. Greer, L. Valdevit and W. B. Carter, Ultralight Metallic Microlattices, Science, vol. 334, pp. 962-965, 2011.

plates) unchanged[5]. On the other hand, one might need a lower flexural strength for specific applications, with the same lineic and/or surfacic masses. This can be achieved with strand structures, i.e. by creating topological interfaces in the material.

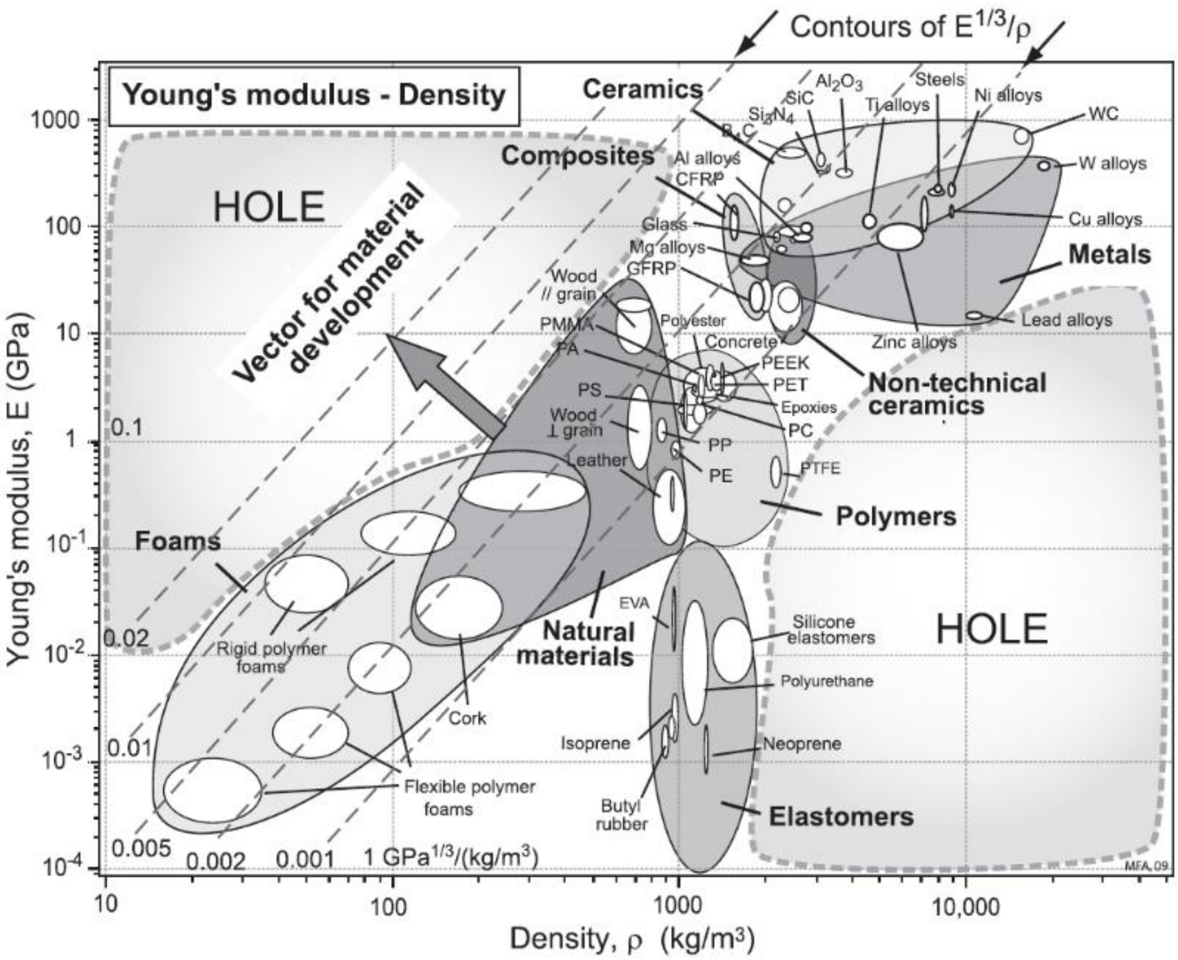

Fig.1: Material performance map for Young's modulus, taken from[6]

Architectured materials thus lie between the microscale and the macroscale. This class of materials involves geometrically engineered distributions of microstructural phases at a scale comparable to the scale of the component, thus calling for enriched models of continuum mechanics, i.e. generalized continua theories, in order to describe the behaviour of architectured materials, strain-gradient elasticity[7], and strain-gradient plasticity for instance. This topic has been especially fruitful these last few years for the French mechanics of materials community ; this results in the availability of versatile models able to describe the various situations encountered with architectured materials. Given mature processing techniques, architectured materials are promised to a bright future in industrial applications due to their enticing customisable and multifunctional specific properties.

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[5] P. Weaver and M. F. Ashby, The Optimal Selection of Material and Section-shape, Journal of Engineering Design, vol. 7, no. 2, pp. 129-150, 1996.

[6] M. Ashby, Designing Architectured Materials, Scripta Materialia, vol. 68, no. 1, pp. 4-7, 2013.

[7] N. Auffray, J. Dirrenberger and G. Rosi, A complete description of bi-dimensional anisotropic strain-gradient elasticity, International Journal of Solids and Structures, vol. 69, pp. 195-210, 2015.

Capitalising on the concepts of architectured materials, our group at Laboratoire PIMM explored the potential applications of large-scale 3D printing techniques to civil engineering structures, based on a collaboration with the ENSA Paris-Malaquais Digital Knowledge department, lead by Philippe Morel, and INRIA (French national research center for computation and automation), through the DEMOCRITE project, which was funded by HESAM Université for 150k€.

Fig.2: UHPC 3D printing[8]

Until recently, additive manufacturing (AM) techniques were confined to high value adding sectors such as the aeronautical and biomedical industries, mainly due to the steep cost of primary materials used for such processes. In the last decade, the development of large-scale AM in such domains as design, construction and architecture, using various materials such as polymers, metals and cementitious materials. The deposition process developed in the project was designed for cement-based 3D printing.

Based upon an understanding of the limitations identified in previous projects present in the literature, the DEMOCRITE project dealt with the large-scale additive manufacturing of selective deposition for ultra-high performance concrete (UHPC). The 3D involved printing process is based on a FDM-like technique, in the sense that a material is deposited layer by layer through an extrusion printhead. The project also explored the possibilities offered by computer-aided design (CAD) and optimisation, and their integration within the product design process in the case of large-scale AM. Thus, the introduced technology succeeded in solving many of the problems that could be found in the literature. Most notably, the process enabled the production of 3D large-scale complex geometries, without the use of temporary supports, as opposed to 2.5D examples found in the literature for concrete 3D printing. Multifunctionality enabled by arbitrary complex geometry is studied for a large-scale structural element.

The DEMOCRITE project was designed upon the following challenge: developing a large-scale additive manufacturing technology capable of producing multifunctional structural elements with increased performance. With this work, the aim of our group was also to take part in the redefinition of architecture and design in the light of integral computation and fully automated processes. The

[8] C. Gosselin, R. Duballet, P. Roux, N. Gaudillière, J. Dirrenberger ans P. Morel, Large-scale 3D printing of ultra-high performance concrete–a new processing route for architects and builders, Materials and Design, vol. 100, pp. 102-109, 2016. and XtreeE, http://www.xtreee.com

results of the DEMOCRITE project, including tangential continuity slicing, optimization for low thermal conductivity, as well as actual built structural elements, were published in Materials & Design[9]. An example of the structures developed and printed in DEMOCRITE is shown on Fig.2, along with a more recent construction by XtreeE[10]. As a continuation of the project, a spin-off company, XtreeE, was created in order to develop and commercialise the 3D printing technology introduced.

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[9] C. Gosselin, R. Duballet, P. Roux, N. Gaudillière, J. Dirrenberger ans P. Morel, Large-scale 3D printing of ultra-high performance concrete–a new processing route for architects and builders, Materials and Design, vol. 100, pp. 102-109, 2016.

[10] XtreeE, http://www.xtreee.com